Homogenization of Daily Temperatures over Canada

LUCIE A. VINCENT AND X. ZHANG

Climate Research Branch, Meteorological Service of Canada, Downsview, Ontario, Canada

B. R. BONSAL

National Water Research Institute, Saskatoon, Saskatchewan, Canada

W. D. HOGG

Climate Research Branch, Meteorological Service of Canada, Downsview, Ontario, Canada

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ABSTRACT

A method to homogenize daily maximum and minimum temperatures over Canada is presented. The procedure is based on previously defined monthly adjustments derived from step changes identified in annual Canadian temperature series. Daily temperatures are adjusted by incorporating a linear interpolation scheme that preserves these monthly adjustments. The temperature trends and variations present in the homogenized monthly and annual datasets are therefore preserved. Comparisons between unadjusted and adjusted daily temperatures at collocated sites show that the greatest impact of the adjustments is on the annual mean of the daily maximum and minimum temperatures with little effect on the standard deviation. The frequency and distribution of the extremes are much closer to those provided by the target observations after adjustments. Furthermore, the adjusted daily temperatures produced by this procedure greatly improve the spatial pattern of the observed twentieth century extreme temperature trends across the country.

1. Introduction

During the past several years, considerable effort has been devoted toward the identification and adjustment of inhomogeneities in climatological time series. The prime objective was to prepare datasets that can be used with confidence in the analyses of trends, climate variability, and climate change. Long-term climatological records often contain variations caused by changes in site exposure, location, instrumentation, observer, and observing procedures. As a result, artificial variations that are totally unrelated to changes in climate can be introduced into the time series. Rigorous examination of climatological datasets and adjustment for data problems are therefore necessary for the proper detection and understanding of climate change.

Many techniques have been developed for the identification and adjustment of inhomogeneities in climatological datasets (see Peterson et al. 1998 for a detailed review). Most are based on relative homogeneity that involves the comparison of a candidate series with a reference series. Several techniques have addressed various homogenization issues and their approaches have differed depending on the type of observations, station density, ability to create a reference series, and availability of metadata. Pioneering works in the homogenization of long temperature datasets include the procedures developed by Jones et al. (1986) and Karl and Williams (1987). More recently, homogenization techniques have used statistical approaches to identify the most probable data of each inhomogeneity in the absence of prior knowledge of the time of change. Some statistical techniques are based on maximum likelihood approaches (Alexandersson 1986), regression models (Easterling and Peterson 1995; Vincent 1998), or Bayesian procedures (Perreault et al. 1999). Many tests assume the reference series to be homogeneous and much effort went into the creation of a suitable reference series (Peterson and Easterling 1994). However, studies are currently underway to assess techniques that do not require homogeneous reference series (Caussinus and Mestre 1996; Szentimrey 1999). Most homogenization techniques have been applied to temperature series although other variables such as precipitation (Alexandersson 1986; Perreault et al. 1999) and mean surface air pressure (Slonosky et al. 1999) have also been examined. In spite of the different approaches and ad-

Corresponding author address: Lucie A. Vincent, Meteorological Service of Canada, 4905 Dufferin St., Downsview, ON M3H 5T4, Canada.
E-mail: lucie.vincent@ec.gc.ca

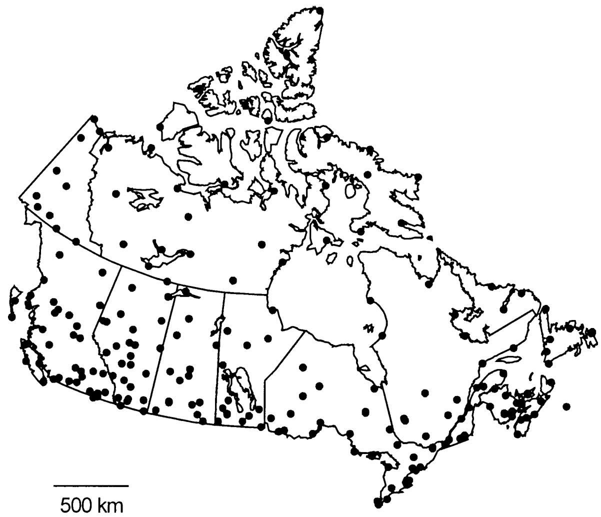

FIG. 1. Location of the 210 stations with homogenized temperature data.

justment philosophies, it is a general consensus that the purpose of homogenized climatological datasets is not to replace archived observations, but rather to create datasets suitable for climate change analyses.

A technique was recently developed for the identification of inhomogeneities in Canadian annual temperature time series (Vincent 1998). It consisted of the application of regression models to determine if the candidate series was homogeneous (no adjustment required), or if inhomogeneities (artificial steps and trends) were present. Annual mean maximum and minimum temperatures were tested separately using this technique and monthly adjustments were applied to the time series. This resulted in the creation of homogenized monthly temperature datasets (Vincent and Gullett 1999) for 210 locations across the country (Fig. 1). Whenever possible, the likely causes of the inhomogeneities were retrieved through historical evidence such as the inspector's reports. Note that adjustments have only been carried out for identified step changes and the homogenized monthly temperatures have not been adjusted for artificial trends at this time.

Homogeneity assessment of the maximum and minimum temperatures at the 210 Canadian stations revealed that about 40% of the series were homogeneous while 60% contained 1–4 steps mainly due to station relocation and changes in observing procedures. Few stations were homogenous in both maximum and minimum temperatures and physical changes did not necessarily result in identical inhomogeneities in both series. Some of the steps were caused by the joining of short-term station segments. These included the joining of observations from an original site to an airport site (frequently during the 1940s), and the joining of human and automated observations (during the 1990s). Since it is expected that automated stations will continue to replace manned stations, mathematical procedures are needed to assemble these data in order to produce reliable long-term climatological time series.

Most of Canada's temperature homogeneity analysis has been carried out on annual and monthly timescales with relatively little consideration given to daily adjustments. Several studies have clearly identified the need for homogenized daily datasets to analyze changes in the frequency and intensity of extreme climate events (e.g., Folland et al. 1999; Jones et al. 1999). Homogenized daily temperatures have also been requested for the validation of general circulation models (Zwiers and Kharin 1998). Daily temperature adjustments present a new level of complexity mainly due to the high variability inherent in daily data, and the potential need for individual adjustments to each day (e.g., a change in instrument's exposure can result in a different adjustment depending whether it is a sunny, cloudy, or windy day).

The purpose of this paper is to present a methodology for the adjustment of daily maximum and minimum temperatures. Section 2 provides the daily adjustment methodology, including a brief overview of previously derived annual and monthly adjustments. In section 3, changes in the daily temperature distribution and in temperature extremes (caused by the daily adjustments) are assessed through the comparison of collocated sites with 10 yr of overlapping data. Further assessment is carried out in section 4 that presents the impact of the daily adjustments on the observed trends in the frequency of temperature extremes over Canada. A discussion and conclusion then follow in sections 5 and 6, respectively.

2. Methodology

As mentioned previously, the adjustments of temperature at the daily timescale can be difficult mainly due to the high variability of the daily observations. The preferred methodology would be to develop procedures based on each cause of inhomogeneity. However, this would be a very site-specific task that would be nearly impossible to implement on a Canada-wide basis (see discussion in section 5). In the previous homogeneity assessment of the Canadian stations (Vincent and Gullett 1999), steps due to station relocation and changes in observing procedures were found in 60% of the annual time series. It is believed that the daily temperatures should at least be adjusted for these inhomogeneities. As a result, the daily datasets are corrected to reflect the same temporal variations as those present in the homogenized annual and monthly series. In order to facilitate the description of the daily adjustment methodology, an overview of the identification of inhomogeneities in the annual series and of the monthly adjustments is first provided.

a. Annual and monthly adjustments

Inhomogeneities were first identified in annual mean maximum and minimum temperature time series (Vin-

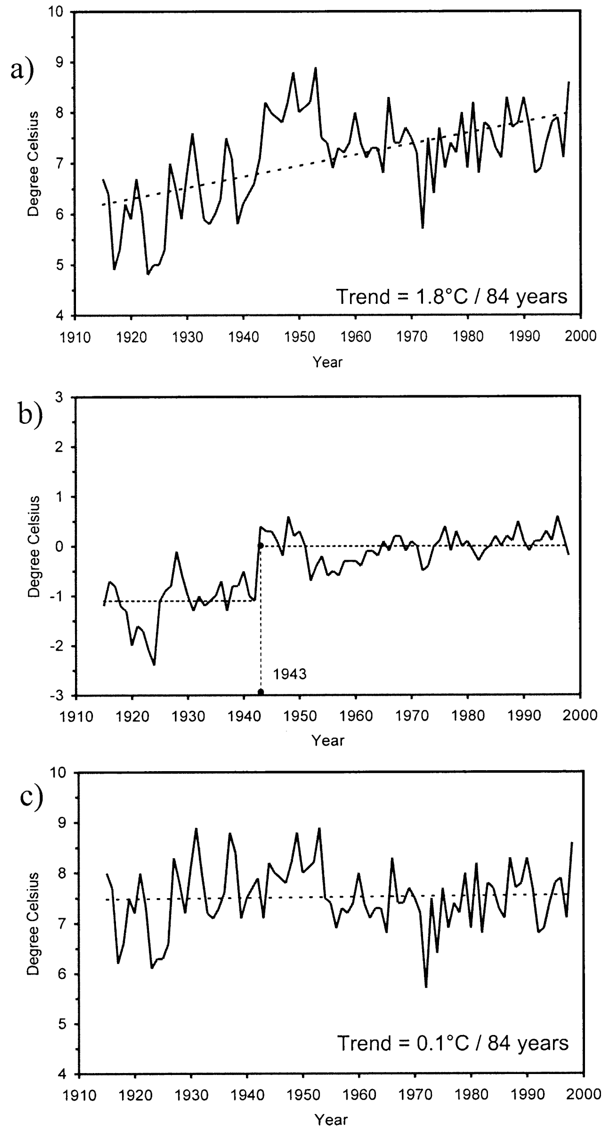

FIG. 2. (a) Annual mean maximum temperature for Mont Joli, Québec, 1915–98; (b) difference between the annual mean maximum temperature and the reference series: a step of 1.1°C is identified in 1943; (c) adjusted annual mean maximum temperature.

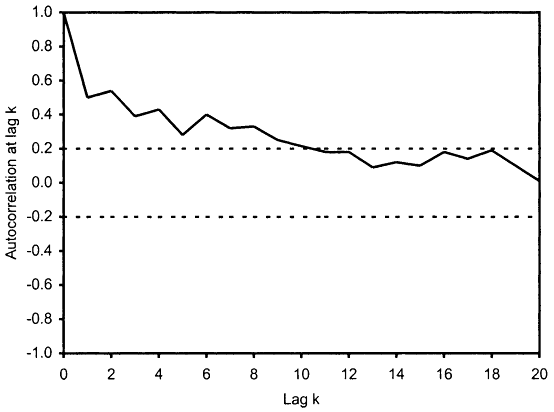

FIG. 3. Autocorrelation of the residuals at different lags after fitting model 1 to the annual mean maximum temperature of Mont Joli, 1915–98. The dashed lines represent the approximate 95% confidence interval.

cent 1998). Annual temperature anomalies from the 1961–90 reference period were obtained at a candidate station and at a number of surrounding stations. A reference series was then produced by averaging the anomalies of the surrounding stations. To determine if the candidate series was homogeneous, model 1 was applied to the datasets as follows:

$$y_i = a_1 + c_1 x_i + e_i \qquad i = 1, \ldots, n, \tag{1}$$

where y_i are anomalies of the candidate series, x_i are the anomalies of the reference series, and i is the time step. The autocorrelations of the residuals e_i were computed for several lags. If they were not significantly different from zero, the candidate series was considered homogeneous. Conversely, significant autocorrelations at several consecutive low lags indicated a nonhomogeneous candidate series.

To identify the position and magnitude of a step in the annual temperature series, model 2 was applied to the annual anomalies as follows:

$$y_i = a_2 + b_2 I + c_2 x_i + e_i \qquad i = 1, \ldots, n$$

$$I = \begin{cases} 0 & \text{for } i = 1, \ldots, p - 1 \\ 1 & \text{for } i = p, \ldots, n. \end{cases} \tag{2}$$

The change point p indicates the position in time of a step. Since the position of the step was not known in advance, model 2 was fitted successively for several values of p. The minimum sum of square errors (SSE) indicated the best fit of model 2. The corresponding p was the estimated position of the step and the parameter b_2 was its estimated magnitude.

For example, annual mean maximum temperatures at Mont Joli, Québec, Canada, were assessed for the period 1915–98 (Fig. 2a). The original series showed a trend of 1.8°C over the 84 yr of observations. The application of model 1 revealed that the autocorrelations of the residuals were significantly different from zero at many consecutive low lags (Fig. 3). Model 2 determined a minimum SSE in 1943 (Fig. 4) and a step in the annual series of 1.1°C. Differences between the annual mean maximum temperatures at Mont Joli and the reference series clearly illustrate the step in 1943 (Fig. 2b). Base and reference series were then divided at 1943. Each segment was retested separately and both intervals were founded to be homogeneous.

Monthly adjustments were obtained by applying model 2 to the time series of the 12 individual months for the p identified in the annual series. The monthly adjustments therefore correspond to the magnitude of the step given by the parameter b_2 for each month. For the example of Mont Joli, the monthly adjustments corre-

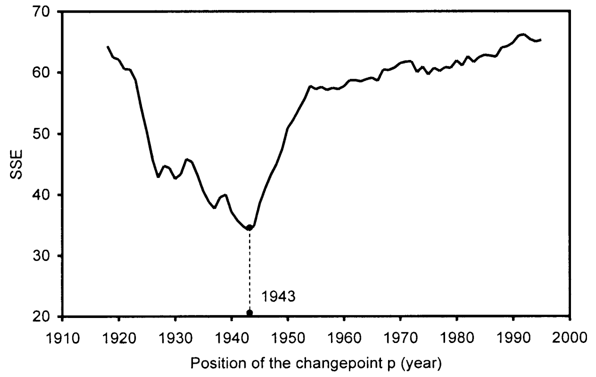

FIG. 4. Sum of square errors obtained from fitting model 2 with change point *p*.

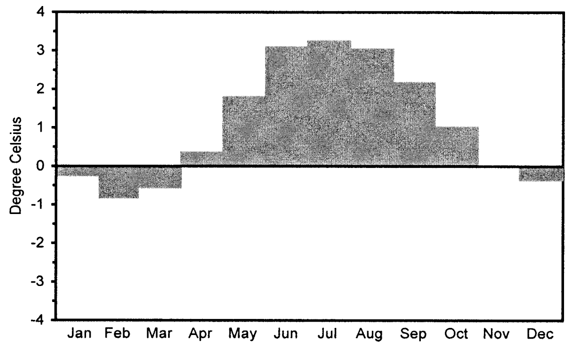

FIG. 5. Monthly adjustments for the step of 1.1°C in 1943 at Mont Joli.

sponding to 1943 are given in Fig. 5. The adjustments vary considerably from month to month with values greater than 3.0°C over the summer, and slightly negative during the winter. The adjustments were applied on the monthly time series to bring the segment 1915–42 into agreement with 1943–98, the most recent homogeneous part of the series. The annual mean maximum temperatures were then recalculated from the adjusted monthly values. The adjusted annual time series shows a trend of only 0.1°C over 84 yr (Fig. 2c). Similar increases are also observed in the neighboring stations.

The step of 1.1°C identified in 1943 corresponds to the joining of 2 station segments, namely, Pointe au Père, Québec (1915–42), with Mont Joli A (1943–98). Both stations are located along the St. Lawrence River and are less than 20 km apart. At the first station, the observations were taken by a volunteer observer. Mont Joli A is an airport station with the instruments located on the roof of the main terminal building. There was no grass beneath the screen, only a dark veneer, which explains the much warmer temperatures at Mont Joli A during the summer months. In 1967, the instruments were moved to a grass area. This relocation has not created a decreasing step in the annual or monthly time series as expected, and other factors could have been involved to obscure the effects of the 1967 relocation. This relocation of the instruments certainly requires further attention but, for now, the segment 1915–42 is the only interval adjusted because 1943 was the only step objectively identified by the methodology.

b. Daily adjustments

Three approaches are considered for the adjustment of the daily temperatures. The first one is to simply apply the monthly adjustments directly to the daily temperatures. However, this approach resulted in artificial discontinuities at the beginning and end of each month. For Mont Joli, the last few days of March would be adjusted by -0.6°C and the first few days of April by 0.4°C (Fig. 5). The second approach is based on the procedure used to obtain the monthly adjustments. Model 2 is applied to each individual daily series for the change point *p* identified in the annual series in order to produce 365 daily adjustments (Fig. 6). The main disadvantages of this approach are that the adjustments are subject to substantial variability. Furthermore, they require a homogeneous daily reference series that is difficult to produce since inhomogeneities can also be found in the daily temperatures of the surrounding stations. The last approach is based on an interpolation procedure by Sheng and Zwiers (1998). Their main objective was to provide an improved time-interpolation scheme that preserves monthly means and does not yield artificial steps at the joining of calendar months. This approach was chosen to adjust the Canadian daily maximum and minimum temperatures and it is described as follows.

Daily adjustments are derived from the monthly adjustments. They are obtained by linear interpolation between midmonth "target" values that are objectively chosen so that the average of the daily adjustments over a given month is equal to the monthly adjustment. The target values are related to the monthly adjustments by the following system of equations:

$$\mathbf{AT} = \mathbf{M},$$

where $\mathbf{A}$ is a tridiagonal 12×12 matrix,

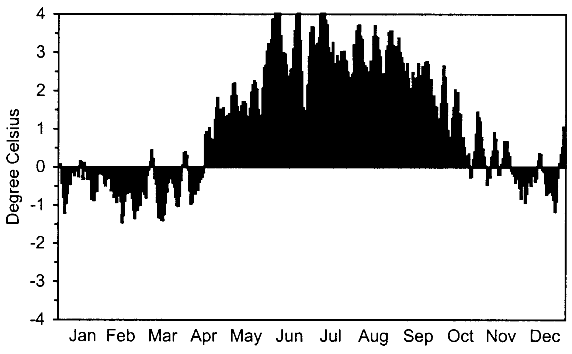

FIG. 6. Daily adjustments by regression for the step of 1.1°C in 1943 at Mont Joli.

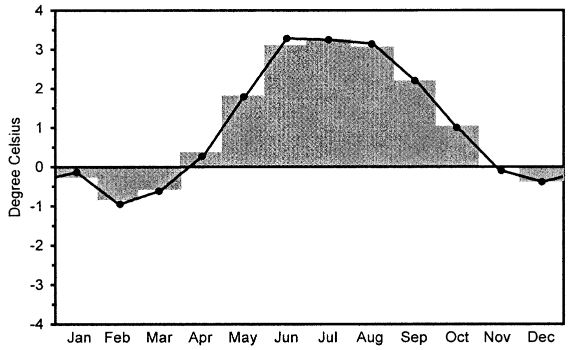

FIG. 7. Monthly adjustments (in gray), target values (black dots), and daily adjustments by interpolation (black line) for the step of 1.1°C in 1943 at Mont Joli.

$$\mathbf{A} = \begin{vmatrix} 7/8 & 1/8 & & & \\ 1/8 & 6/8 & 1/8 & & \\ & \cdot & \cdot & \cdot & \\ & & 1/8 & 6/8 & 1/8 \\ & & & 1/8 & 7/8 \end{vmatrix}.$$

Here **T** is a 12 × 1 vector of the target values and **M** is a 12 × 1 vector of the monthly adjustments. Sheng and Zwiers (1998) have produced the tridiagonal matrix **A** by developing a system of equations for measuring the area under the piecewise linear interpolation function given over the 12 monthly means. The target values are then obtained by solving the equations:

$$\mathbf{T} = \mathbf{A}^{-1}\mathbf{M}. \qquad (3)$$

For the example of Mont Joli, daily adjustments for the step identified in 1943 are computed as follows. First, the target values are obtained by using Eq. (3). Then, interpolation lines are obtained between each target value. The daily adjustments thus correspond to the equally spaced points on the lines (Fig. 7). These daily adjustments show less variation over the year than those produced by regression (Fig. 6). Nevertheless, they still capture the large positive adjustments over the summer and the slightly negative adjustments during the winter.

This procedure has several advantages over the other two approaches. It does not create artificial discontinuities at the joining of the calendar months and does not require homogeneous daily reference series for comparison purpose. In addition, the procedure does not involve the detection of inhomogeneities in daily temperature series, which can be difficult due to the high variability in the daily observations. Finally, the adjusted daily temperatures preserve the same long-term trends and variations as those present in the adjusted monthly and annual time series.

3. Assessment of daily adjustments

The daily adjustments described in section 2 contain two sources of error. First, since the procedure is based on previously defined monthly adjustments (Vincent 1998), any errors introduced in the monthly adjustments will also be apparent in the daily adjustments. The second involves errors introduced by the interpolation technique itself. This section focuses only on those errors created by the interpolation procedure. In this way, the interpolation approach is evaluated independently from the method used to produce the monthly adjustments.

The assessment is carried out at eight different stations for either maximum or minimum temperatures (Table 1). These stations were specially selected since a step was identified in either the annual mean maximum or the annual mean minimum temperature series due to the joining of two segments of observations taken from two collocated sites. In addition, both sites have observations over a 10-yr common period following the identified step. Daily adjustments are assessed using the daily temperatures of both sites over the common interval. Errors produced by the monthly adjustments are not considered in this assessment. The observed monthly differences between the collocated sites are calculated and averaged over the 10 yr and they are used as monthly adjustments. The daily adjustments are then obtained from the interpolated line between the target values derived from the observed monthly differences using the procedure in section 2b. The daily adjustments are applied to the observed daily temperatures of site 1 for comparison with the observed daily temperatures of site 2.

TABLE 1. Mean and std dev (°C) of daily temperatures at site 1, adjusted site 1, and site 2.

Stations (site 1/site 2)	Province	Overlapping period	Temperature	Daily temperature site 1		Daily temperature adjusted site 1		Daily temperature site 2	
				Mean	Std dev	Mean	Std dev	Mean	Std dev
Fairview/Peace River A	Alta	1959–68	Min	−3.7*	12.5*	−5.9	13.3	−5.9	13.5
The Pas/The Pas A	Man	1948–57	Max	5.5	15.7	5.0	15.5	5.0	15.5
Gore Bay/Gore Bay A	Ont	1947–56	Min	−0.1*	11.2	1.5	11.1	1.5	10.9
Owen Sound/Wiarton A	Ont	1947–56	Max	12.9*	11.3	11.4	11.0	11.4	11.0
Pointe au Père/Mont Joli A	Qué	1943–52	Max	6.8*	10.4*	8.1	11.6	8.1	11.9
Grand Falls/Aroostook	NB	1929–38	Max	9.3*	12.4	10.3	12.4	10.3	12.5
Moncton/Monton A	NB	1939–48	Min	−1.5*	10.6	−0.1	10.8	−0.1	10.4
Deer Lake/Deer Lake A	Nfld	1965–74	Min	−0.3*	9.5	−1.8	9.6	−1.8	9.8

* Significant differences between site 1 and site 2, and between adjusted site 1 and site 2 at the 0.05 level.

TABLE 2. Mean and std dev of the daily errors, and mean and std dev of the daily errors in absolute value (°C) between site 1 and site 2, and between adjusted site 1 and site 2.

	Daily error between site 1 and site 2				Daily error between adjusted site 1 and site 2			
Stations (site 1/site 2)	Mean	Std dev	Mean absolute values	95th percentile absolute values	Mean	Std dev	Mean absolute values	95th percentile absolute values
Fairview/Peace River A	−2.3	2.7	2.6	7.7	0.0	2.5	2.0	4.9
The Pas/The Pas A	−0.5	1.6	1.1	3.3	0.0	1.6	1.1	3.1
Gore Bay/Gore Bay A	1.7	2.4	2.1	5.6	0.0	2.3	1.6	4.7
Owen Sound/Wiarton A	−1.5	2.3	1.9	5.6	0.0	2.3	1.5	4.9
Pointe au Père/Mont Joli A	1.3	3.0	2.1	7.2	0.0	2.7	1.7	5.6
Grand Falls/Aroostook	1.0	2.6	2.0	6.1	0.0	2.6	1.7	5.8
Moncton/Monton A	1.4	2.7	2.2	6.1	0.0	2.7	2.0	5.2
Deer Lake/Deer Lake A	−1.5	2.6	2.1	6.6	0.0	2.6	1.9	5.5

For example, a step of −2.3°C was identified in 1959 in annual mean minimum temperature series due to the joining of two segments of observations, namely Fairview and Peace River A, Alberta, Canada (Table 1). Both sites also have daily observations for the period 1959–68. The daily adjustments are derived from the 10-yr monthly differences between both sites (as opposed to using the monthly adjustments provided by the regression procedure). The daily adjustments are applied to the temperatures of Fairview for comparison to the daily observations of Peace River A over the 1959–68 interval.

a. Changes in daily temperature distribution

To determine how the adjustments affect the daily temperature distribution, the 10-yr mean and standard deviation at site 1 and adjusted site 1 are compared to those from site 2 using the t test and F test, respectively (Neter et al. 1985). Results are presented in Table 1. In seven cases, the mean of the daily temperatures before adjustment is significantly different from that at site 2. Following the adjustments, there are no significant differences (due to the nature of the procedure). The standard deviations are significantly different in only two cases before adjustment. Changes in the mean caused by the daily adjustments vary from −2.3° to 1.7°C over the 8 cases, while changes in the standard deviation are much smaller, ranging from −0.3° to 1.2°C. These results indicate that the daily adjustments have significantly affected the mean of the daily temperature distribution, but they have not considerably changed the shape of the distribution.

The daily errors are also closely examined. These are determined by calculating the differences in daily temperatures between site 1 and site 2, and between adjusted site 1 and site 2. Table 2 provides the 10-yr mean and standard deviation for the same eight stations. Since positive and negative errors tend to cancel each other, the 10-yr mean and 95th percentiles in Table 2 are also computed from the daily errors in absolute value. As shown in Table 1, the daily error mean between both sites varies from −2.3° to 1.7°C over the 8 cases, and it becomes 0°C with the adjustments. The standard deviation of the daily errors remain the same or are slightly smaller. The most convincing improvement due to the daily adjustments is evident in the absolute values. In most cases, the mean and 95th percentile of these values are considerably smaller following the adjustments. This signifies that on a daily basis, the adjusted temperature is much closer to the target daily value (as provided by site 2). However, this assessment also suggests that on

TABLE 3. Percentage of days with minimum or maximum temperature below the 5th percentile and above the 95th percentile (given as an average over 10 yr) at site 1, adjusted site 1, and site 2, respectively. The 5th and 95th percentiles are 10-yr averages of the percentiles obtained at site 2.

				Site 1		Adjusted site 1		Site 2	
Stations (site 1/site 2)	Province	Overlapping period	Temperature	<5th percentile	>95th percentile	<5th percentile	>95th percentile	<5th percentile	>95th percentile
Fairview/Peace River A	Alta	1959–68	Min	1.7	8.5	4.3	4.7	4.8	5.1
The Pas/The Pas A	Man	1948–57	Max	4.9	5.0	5.1	3.8	4.8	4.9
Gore Bay/Gore Bay A	Ont	1947–56	Min	8.0	3.2	5.7	7.0	5.1	5.2
Owen Sound/Wiarton A	Ont	1947–56	Max	2.9	8.9	4.4	5.6	4.8	4.7
Pointe au Père/Mont Joli A	Qué	1943–52	Max	4.8	0.5	4.8	2.9	5.2	4.5
Grand Falls/Aroostook	NB	1929–38	Max	6.7	2.2	4.5	4.4	5.1	4.4
Moncton/Monton A	NB	1939–48	Min	6.8	4.3	5.8	7.3	5.1	5.0
Deer Lake/Deer Lake A	Nfld	1965–74	Min	3.6	8.6	5.0	4.7	5.5	5.1

TABLE 4. Comparison of extreme warm or extreme cold temperature distribution between site 1 and site 2, and between adjusted site 1 and site 2.

Stations (site 1/site 2)	Province	Overlapping period	Extreme temperature	Site 1 and site 2		Adjusted site 12 and site 2	
				D	*p* value	*D*	*p* value
Fairview/Peace River A	Alta	1959–68	Cold	0.70	0.00*	0.33	0.03*
The Pas/The Pas A	Man	1948–57	Warm	0.20	0.39	0.17	0.59
Gore Bay/Gore Bay A	Ont	1947–56	Cold	0.40	0.01*	0.27	0.14
Owen Sound/Wiarton A	Ont	1947–56	Warm	0.37	0.02*	0.17	0.59
Pointe au Père/Mont Joli A	Qué	1943–52	Warm	0.93	0.00*	0.48	0.00*
Grand Falls/Aroostook	NB	1929–38	Warm	0.37	0.02*	0.20	0.39
Moncton/Monton A	NB	1939–48	Cold	0.47	0.00*	0.30	0.07
Deer Lake/Deer Lake A	Nfld	1965–74	Cold	0.37	0.02*	0.27	0.14

* Distributions that are statistically different at the 0.05 level.

average, a daily error of 1.1° to 2.0°C can remain after adjustments, and that the daily error can still be as large as 3.1° to 5.8°C in extreme cases.

b. Changes in temperature extremes

Another important aspect in the examination of temperature at the daily timescale includes extreme temperatures, and more importantly, the frequency of these extremes. Table 3 presents the percentage of days with minimum or maximum temperature below the 5th and above the 95th percentiles, respectively. The percentage of days refers to a 10-yr percentage average obtained from site 1, adjusted site 1, and site 2. The 5th and 95th percentiles are the 10-yr percentiles averages calculated at site 2 only and they are used for comparison purposes. The results show an improvement in the number of extremes following the adjustments. The frequency is at times slightly underestimated (e.g., extreme warm days of Pointe au Père/Mont Joli A), or slightly overestimated (e.g., extreme cold days of Moncton/Moncton A, New Brunswick, Canada). A procedure based on variable adjustments for individual days may improve these situations. Nonetheless, the interpolation procedure still produces reasonable estimates of the temperature extreme frequencies.

The statistical distribution of the extremes is also examined. Extreme warm temperatures are defined as the three highest daily maximum temperatures during the year. Similarly, extreme cold temperatures are the three lowest daily minimum temperatures. This provides samples of 30 extreme values at each site for the 10-yr comparison. Distributions between site 1 and site 2, and between adjusted site 1 and site 2 are compared using the Kolmogoroff–Smirnoff test (Sachs 1984) to determine if both samples are drawn from the same distribution. Cumulative frequencies are obtained and a D statistic is calculated. The p value is the probability of exceeding D under the hypothesis H_0 (both samples belong to the same distribution) and the level of significance used is 0.05.

Table 4 shows that before adjustment, the extreme temperature samples of site 1 and site 2 are not from the same distribution in seven cases. These correspond to the significant daily mean differences between site 1 and site 2 (Table 1). Following the adjustments, there are only two cases with samples from different distributions. These results demonstrate that the daily adjustment procedure has improved the extreme temperature distribution. The results also imply that using daily temperature series that are not adjusted for artificial variations could possibly affect the correct assessment of trends in extreme temperatures.

4. Impact of adjustments on extreme temperature trends

The impact of daily adjustments is further assessed by comparing the before and after adjustment trends in the frequency of extreme low and extreme high temperatures at each of the 210 individual sites. Extreme low temperatures are represented by the percentage of days with minimum temperature below the 5th percentile (relative to the 1961–90 reference period), while extreme high temperatures are the percentage of days with maximum temperature above the 95th percentile. Figure 8 provides seasonal trends for Mont Joli for the period 1915–98. The figure shows that the impact of the adjustments varies considerably depending on the season. For example, the winter extreme high temperature trend (Fig. 8a) has increased from 2.3% to 3.3% (2 to 3 days) over the 84-yr period. This is due to the daily winter adjustments having reduced the maximum temperatures during the period 1915–42 (Fig. 7). On the other hand, trends have decreased from 4.7% to 2.2% and from 6.1% to 3.1% during spring and summer (Figs. 8b and 8c) since adjustments during these seasons have increased most of the daily temperatures. Positive daily adjustments were also applied to the fall resulting in a decreasing trend of 0.4% over the 84 yr (Fig. 8d).

Changes in trends over the entire country are provided on a seasonal basis for various time periods in Table 5. The table shows the percentage of stations with a change in trend (i.e., for which the difference between the trends before and after homogeneity adjustment is different from zero). More stations have experienced changes in

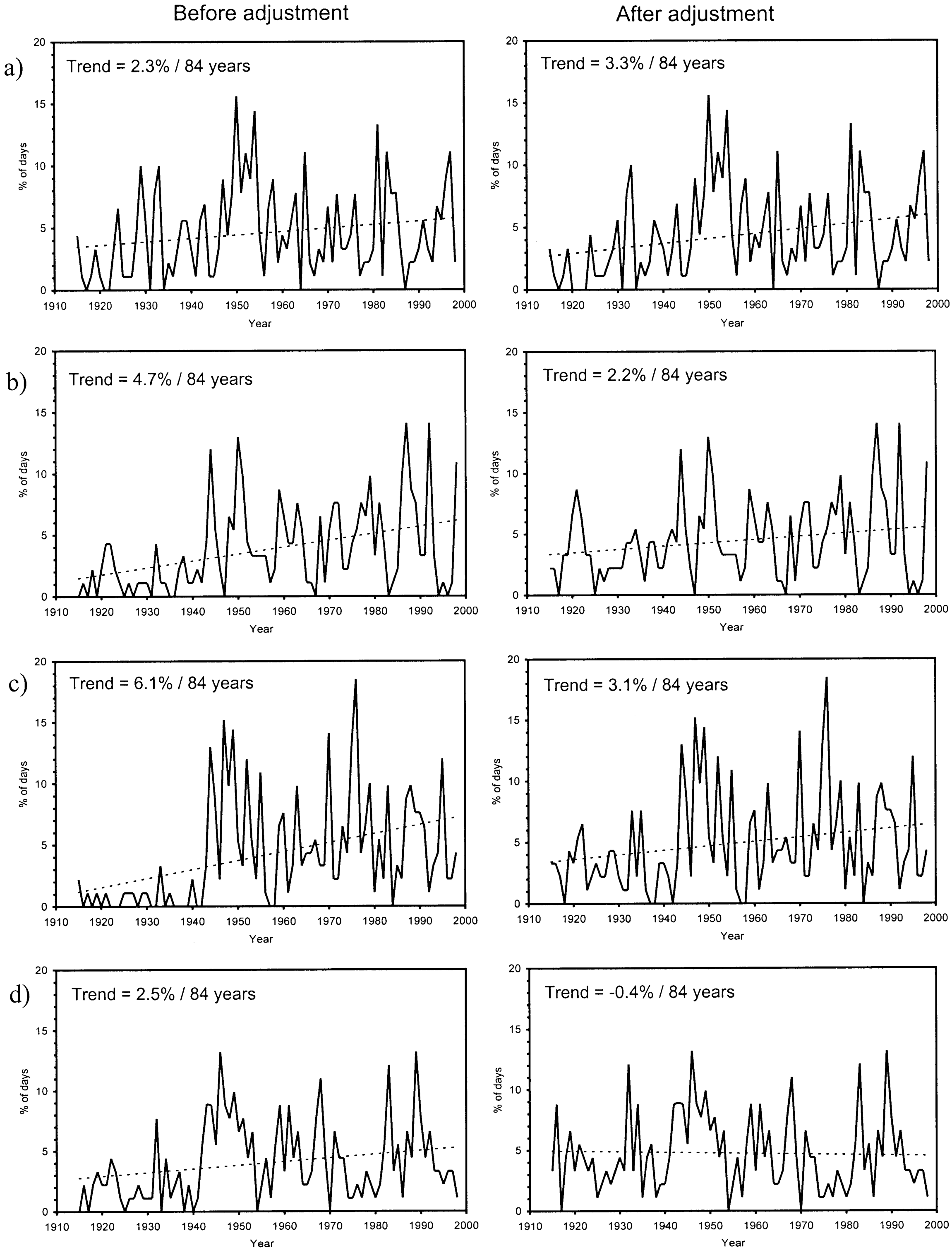

FIG. 8. Percentage of days at Mont Joli with maximum temperature above the 95th percentile before adjustment and after adjustment during the (a) winter, (b) spring, (c) summer, and (d) fall, over the period 1915–98.

TABLE 5. Percentage of stations associated with a change in extreme temperature trend due to the adjustments during winter, spring, summer, and fall.

			Percentage of stations with a change in trend in the percentage of days with minimum temperature <5th percentile			Percentage of stations with a change in trend in the percentage of days with maximum temperature >95th percentile		
Period	No. of stations	Season	Any change	More cold extremes	Less cold extremes	Any change	Less warm extremes	More warm extremes
1950–98	185	Winter	51.4	16.8	34.6	20.5	14.6	5.9
		Spring	49.2	16.8	32.4	23.8	13.5	10.3
		Summer	54.0	16.2	37.8	23.3	14.1	9.2
		Fall	48.7	17.3	31.4	24.8	15.1	9.7
1930–98	147	Winter	62.6	23.1	39.5	40.2	29.3	10.9
		Spring	58.5	23.1	35.4	40.8	27.2	13.6
		Summer	65.3	26.5	38.8	42.2	30.6	11.6
		Fall	59.2	23.8	35.4	40.8	27.2	13.6
1900–98	82	Winter	80.5	30.5	50.0	64.6	50.0	14.6
		Spring	75.6	37.8	37.8	64.6	46.3	18.3
		Summer	80.4	40.2	40.2	70.8	53.7	17.1
		Fall	79.3	36.6	42.7	65.8	46.3	19.5

the frequency of extreme lows as compared to extreme highs since maximum temperatures were found to be more homogenous than minimum temperatures for many stations (Vincent and Gullett 1999). The table also reveals that as the period of record becomes longer, a higher percentage of stations are associated with changes in trends. This is likely due to the fact that more inhomogeneities have been detected and adjusted in the early part of the series (i.e., prior to 1950). In terms of the direction of change, the percentage of stations with less cold extremes is greater than those with more cold extremes. This is attributable to minimum temperature adjustments resulting from a change in the definition of the observing day in 1961 (Vincent and Gullett 1999). This inhomogeneity is discussed further in section 5. For extreme high temperatures, the percentage of stations with less warm extremes is generally higher than those with more warm extremes. The cause of these inhomogeneities varies from station to station.

A comparison of seasonal trends in the frequency of extreme high temperatures from 1950–98 is presented in Fig. 9. Note that only the stations that experienced a change in trend due to the adjustment procedure are shown (see Table 5). The figure mostly displays a random pattern of positive and negative trends that become less pronounced with the adjustments. A greater impact is observed in the trends in extreme low temperatures (Fig. 10) where more than twice the stations have experienced changes (as compared to extreme high temperatures, see Table 5). Generally, there are fewer or smaller positive trends after adjustments in the eastern part of the country during the winter and the spring. During summer, the "before" map shows a mixture of decreasing and increasing trends while the "after" map provides a more spatially coherent pattern of decreasing trends across the country. Once again, most of these changes result from the adjustments applied to the daily minimum temperatures for a change in the definition of the observing day in 1961. During the fall, the magnitude of changes is very small.

Similar results are also found for 1930–98 and 1900–98. The general spatial pattern of trends in the frequency of extremes has not greatly changed with the adjustments across the country except for the summer extreme low temperatures. However, the adjusted datasets display a smoother field and thus provide improved spatial homogeneity over the unadjusted data. A detailed analysis of the daily and extreme temperature characteristics over Canada, based on the homogenized daily temperatures, is presented in Bonsal et al. (2001).

5. Discussion

This paper presents a simple and straightforward methodology toward the development of homogenized daily temperatures over Canada. The resulting adjusted daily temperatures have reduced the magnitude of the daily errors and have improved the spatial distribution of extreme temperature trends. These adjustments do not consider the need for variable adjustments to each individual day. The likely and most accurate solution would be to develop procedures based on each cause of inhomogeneity and to assess the impact on a daily basis. However, this is often impractical since the causes are not often well documented at each site.

For example, there are a number of climatological stations where the instruments were formerly located on the roof of a building, at some airports and schools, and have been moved to nearby ground locations. Comparisons between rooftop and ground daily maximum and minimum temperatures indicate that the radiating temperature of the roof and walls significantly influence the surrounding air temperature (Griffith et al. 2000). Buildings with low-albedo rooftops are usually warm during sunny days with low winds but significantly cooler during cloudy days. To properly adjust the daily temper-

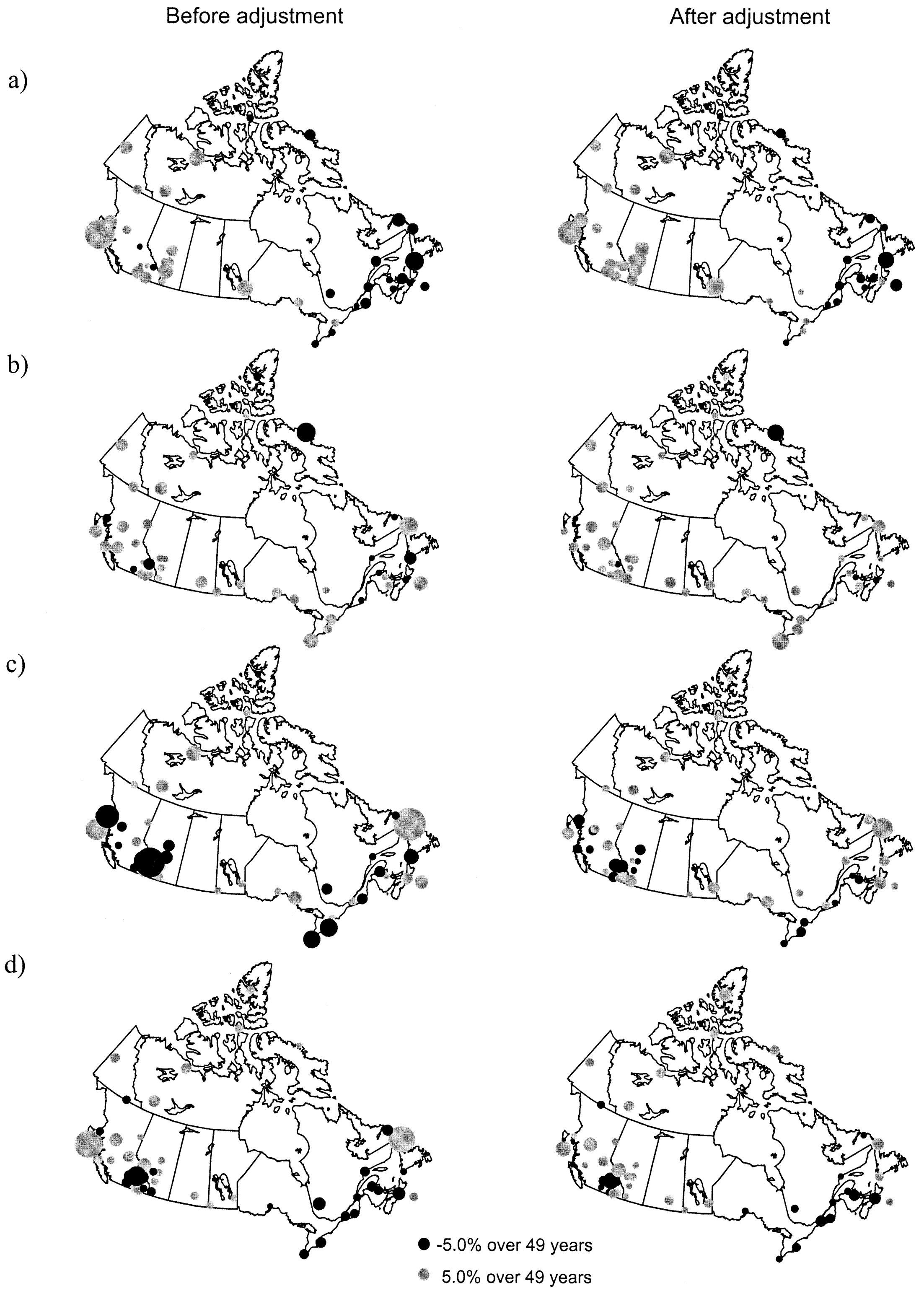

FIG. 9. Trends in the percentage of days with maximum temperatures above the 95th percentile during the (a) winter, (b) spring, (c) summer, (d) fall over the period 1950–98, before and after adjustment, respectively. Gray and black dots indicate positive and negative trends only for stations experiencing a change in trend cause by the adjustment. Size of the dots is proportional to the magnitude of the trend.

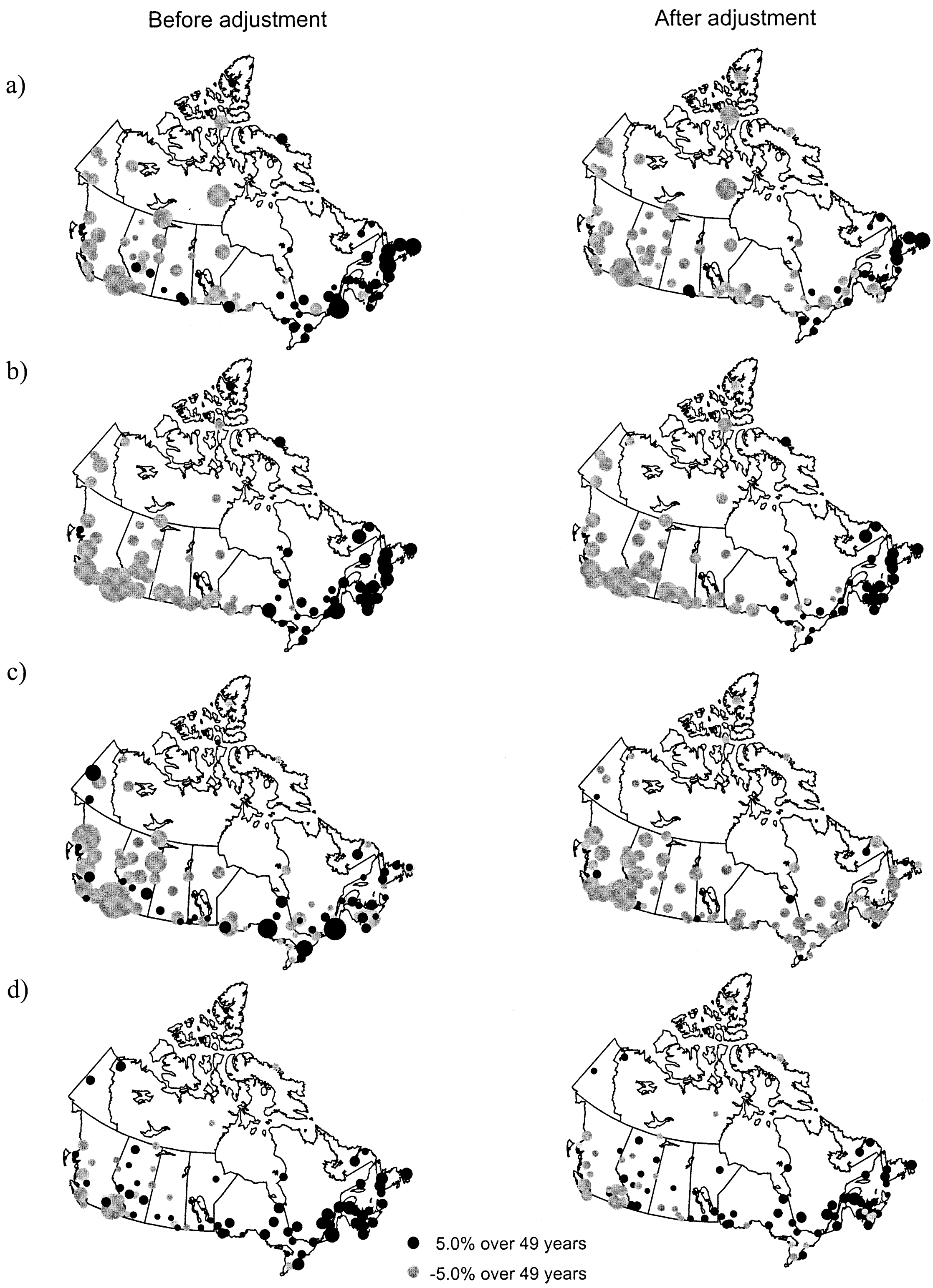

FIG. 10. Trends in the percentage of days with minimum temperatures below the 5th percentile during the (a) winter, (b) spring, (c) summer, (d) fall over the period 1950–98, before and after adjustment, respectively. Gray and black dots indicate negative and positive trends only for stations experiencing a change in trend cause by the adjustment. Size of the dots is proportional to the magnitude of the trend.

atures, additional information such as the solar radiation or cloud cover amounts would be required. However, this type of information is not consistently available in the climatological archives for the station and period concerned, making this refinement to the daily adjustments possible for only a very limited number of stations.

Another inhomogeneity evident in the Canadian temperature time series is due to a redefinition of the observing day in 1961. Daily maximum and minimum temperatures are usually recorded over a 24-h observational window. Changes in the window can introduce a nonclimatic bias to the temperature time series. On 1 July 1961, the climatological day at principal stations in Canada was changed to end at 0600 UTC. Previously, daily measurements were made ending at 0000 UTC. Since 0600 UTC corresponds to the approximate time when the actual minimum temperature occurs in the eastern part of the country, the same minimum was often recorded on two successive days thus leading to more days with lower minimum temperatures. This change resulted in a decreasing step of 0.6°–0.8°C in the annual minimum temperatures at principal stations in eastern Canada at that time (Vincent and Gullett 1999). This inhomogeneity accentuates the cooling trend in the annual minimum temperatures and in the frequency of extreme low temperatures over eastern Canada during the past 50 years (see Fig. 10). Errors in daily temperatures associated with different observing times were also identified at a number of U.S. stations (Karl et al. 1986; DeGaetano 1999; Janis 2000). To improve the adjustment of the daily minimum temperatures due to these types of problems, procedures based on hourly observations would likely be required.

Another potential cause of inhomogeneity in many Canadian temperature series is associated with the ongoing automation of the observing system. Procedures are required to determine if human and automated observations can be joined together in order to create long homogeneous time series. Some Canadian studies have already begun comparing manned and automated daily temperatures and total precipitation at a number of sites across the country (Yip et al. 1999; Milewska 2000; Milewska and Hogg 2002). The objective is to detect the presence of systematic biases, which should be adjusted when combining these observations. Daily adjustments are likely to be improved as results of these types of investigations.

6. Conclusions

A method for the homogenization of daily temperatures is presented. Daily maximum and minimum temperatures over Canada are adjusted for the steps identified in annual time series. The method is simple and straightforward and has several advantages. It does not involve the detection of inhomogeneities in daily temperature series, it does not create artificial discontinuities at the joining of the calendar months, and it preserves the long-term temporal trends and variations as those present in the homogenized monthly and annual datasets. In addition, this approach can also be used with other monthly adjustment techniques commonly cited in the scientific literature for the production of daily temperature adjustments.

Results from the assessment of unadjusted and adjusted daily temperatures at collocated sites indicate that the adjustments resulting from this methodology have improved the daily temperatures. The adjusted daily temperatures were much closer to the target daily values. The mean of the distribution was significantly changed by the adjustments but little effect on the standard deviation was observed (which is essential when segments of observations having same variability are combined). The adjustments have also improved the frequency and the distribution of the temperature extremes. Furthermore, the results show that the adjusted daily temperatures provide a more consistent spatial pattern of the extreme temperature trends over the country.

This methodology provides an important step toward the development of more reliable daily temperatures in Canada. Even if the problem of different day-to-day adjustments is not resolved at this point, the homogenized daily data do show improvements over the archived datasets for the analyses of trends in extremes. As a result, changes in daily variability and in the frequency and intensity of extreme climate events can be analyzed with higher confidence using the homogenized daily data. Future work will involve the ongoing development of procedures to provide more accurate daily adjustments for other homogeneity problems such as the changes in observing times and the joining of human and automated observations.

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REFERENCES

Alexandersson, H., 1986: A homogeneity test applied to precipitation data. *J. Climatol.,* **6,** 661–675.

Bonsal, B. R., X. Zhang, L. A. Vincent, and W. D. Hogg, 2001: Characteristics of daily and extreme temperatures over Canada. *J. Climate,* **14,** 1959–1976.

Caussinus, H., and O. Mestre, 1996: New mathematical tools and methodologies for relative homogeneity testing. *Proc. First Seminar for Homogenization of Surface Climatological Data,* Budapest, Hungary, Hungarian Meteorology Service, 63–72.

DeGaetano, A. T., 1999: A method to infer observation time based on day-to-day temperature variations. *J. Climate,* **12,** 3443–3456.

Easterling, D. R., and T. C. Peterson, 1995: A new method for detecting for undocumented discontinuities in climatological time series. *Int. J. Climatol.,* **15,** 369–377.

Folland, C. K., and Coauthors, 1999: Breakout group C: Temperature indices for climate extremes. *Climatic Change,* **42,** 31–43.

Griffith, B., T. B. McKee, N. J. Doesken, and R. J. Leffler, 2000: A comparison of rooftop and surface temperature observations. Preprints, *12th Conf. on Applied Climatology,* Asheville, NC, Amer. Meteor. Soc., 52–54.

Janis, M. J., 2000: Errors in daily minimum and maximum air temperature induced by observation time. Preprints, *12th Conf. on Applied Climatology,* Asheville, NC, Amer. Meteor. Soc., 74–77.

Jones, P. D., S. C. B. Raper, R. S. Bradley, H. F. Diaz, P. M. Kelly, and T. M. L. Wigley, 1986: Northern Hemisphere surface air temperature variations: 1851–1984. *J. Climate Appl. Meteor.,* **25,** 161–179.

——, E. B. Horton, C. K. Folland, M. Hulme, D. E. Parker, and T. A. Basnett, 1999: The use of indices to identify changes in climatic extremes. *Climatic Change,* **42,** 131–149.

Karl, T. R., and C. N. Williams Jr., 1987: An approach to adjusting climatological time series for discontinuous inhomogeneities. *J. Climate Appl. Meteor.,* **26,** 1744–1763.

——, ——, P. J. Young, and W. M. Wendland, 1986: A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States. *J. Climate Appl. Meteor.,* **25,** 145–160.

Milewska, E. J., 2000: Continuity of precipitation amount observations with automation. Preprints, *12th Conf. on Applied Climatology,* Asheville, NC, Amer. Meteor. Soc., 136–137.

——, and W. D. Hogg, 2002: Continuity of climatological observations with automation—Temperature and precipitation amounts from AWOS (Automated Weather Observing System). *Atmos.–Ocean,* in press.

Neter, J., W. Wasserman, and M. H. Kutner, 1985: *Applied Linear Statistical Models.* 2d ed. Irwin, 1127 pp.

Perreault, L., M. Haché, M. Slivitzky, and B. Bobée, 1999: Detection of changes in precipitation and runoff over eastern Canada and U.S. using a Bayesian approach. *Stochastic Environ. Res. Risk Assess.,* **13,** 201–216.

Peterson, T. C., and D. R. Easterling, 1994: Creation of homogeneous composite climatological reference series. *Int. J. Climatol.,* **14,** 671–680.

——, and Coauthors, 1998: Homogeneity adjustments of *in situ* atmospheric climate data: A review. *Int. J. Climatol.,* **18,** 1493–1517.

Sachs, L., 1984: *Applied Statistics: A Handbook of Techniques.* 2d ed. Springer-Verlag, 707 pp.

Sheng, J., and F. Zwiers, 1998: An improved scheme for time-dependent boundary conditions in atmospheric general circulation models. *Climate Dyn.,* **14,** 609–613.

Slonosky, V. C., P. D. Jones, and T. D. Davies, 1999: Homogenization techniques for European monthly mean surface pressure series. *J. Climate,* **12,** 2658–2672.

Szentimrey, T., 1999: Multiple Analysis of Series for Homogenization (MASH). *Proc. Second Seminar for Homogenization of Surface Climatological Data,* Budapest, Hungary, WMO-TD-962, WMO, 27–46.

Vincent, L. A., 1998: A technique for the identification of inhomogeneities in Canadian temperature series. *J. Climate,* **11,** 1094–1104.

——, and D. W. Gullett, 1999: Canadian historical and homogeneous temperature datasets for climate change analyses. *Int. J. Climatol.,* **19,** 1375–1388.

Yip, T., B. Sheppard, P. Kociuba, and E. Milewska, 1999: Climate network modernization project in Canada. Preprints, *11th Conf. on Applied Climatology,* Dallas, TX, Amer. Meteor. Soc., 54–59.

Zwiers, F. W., and V. V. Kharin, 1998: Changes in the extremes of the climate simulated by CCC GCM2 under CO_2 doubling. *J. Climate,* **11,** 2200–2222.